Spalling in EN1168

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1. Bursting, spalling and splitting: what’s the difference?
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- **Introduction**
  - Transfer of prestress force to the concrete is locally, with high stress concentrations.
  - Principle of Jean Claude Barré de Saint-Venant → prestress force spreads out into a linear stress distribution (anchorage zone).
  - Nonlinear stress distribution in this zone.
  - Complex stress state:
    - High compressive stresses just after the loading point.
    - High tensile stresses perpendicular to the line of action of the force (bursting and spalling).
1. Bursting, spalling and splitting: what’s the difference?

- **Bursting**
  - Spreading of the prestress force causes curved compressive stress trajectories which generates transverse tensile stresses (bursting stresses).
  - Bursting stresses occur along the line of action of the prestress force.
1. Bursting, spalling and splitting: what’s the difference?

- **Bursting**
  - Maximum stress is located at some distance behind the loading point.
  - Possible crack pattern (at release and its growth afterwards):

  ![Diagram showing tensile and compressive stress](image)

  - Tensile stress
  - Compressive stress
1. Bursting, spalling and splitting: what’s the difference?

- **Spalling**
  - Prestress force leads to compressive stress trajectories.
  - Parts of the concrete are not subjected to pressure.
  - Stress discontinuity between the compressed and non-compressed zones results in shear and tensile stresses.
1. Bursting, spalling and splitting: what’s the difference?

- **Spalling**
  - Eccentric prestress: the eccentricity will cause extra curving of the already curved compressive stress trajectories.
    - Area with spalling stresses is bigger.
    - Max. spalling stress is bigger.
  
  - Spalling stresses develop beside the loading point along the border of the member.

![Diagram](image)
1. Bursting, spalling and splitting: what’s the difference?

- **Spalling**
  - Maximum stress is located about mid height at member end.
  - Possible crack pattern (at release and its growth afterwards):
1. Bursting, spalling and splitting: what’s the difference?

- Spalling

  Crack opening is large!

  Crack length is large!
1. Bursting, spalling and splitting: what’s the difference?

- **Splitting**
  - Only in case of prestressing (prestress transfer bond).
  - Stresses occur locally around the tendons.
  - Radial compressive stresses due to, such as:
    - Loose cement paste particles get stuck (failure adhesion)
    - Hoyer effect
    - Lack of fit
  
  → circumferential tensile stresses
1. Bursting, spalling and splitting: what’s the difference?

- **Splitting**
  - Maximum stress is located in the beginning of the transmission zone (original diameter of prestressing steel).
  - Possible crack pattern (at release and its growth afterwards):
    - Splitting cracks and bursting cracks are difficult to distinguish.
1. Bursting, spalling and splitting: what’s the difference?

- How to check bursting, spalling and splitting in the design of the slab?
  - Bursting + splitting:
    Art. 4.3.1.2.2 EN1168: ‘Minimum concrete cover and axis distances of prestressing steel’.
    → $c_{\text{min}}$ to the nearest concrete surface and to the nearest edge of a core.
    → independent of the magnitude of the prestressing (in France ‘chemins de fendage’)
  - Spalling:
    Art. 4.3.3.2.1 EN1168: ‘Resistance to spalling for prestressed hollow core slabs’.
    → formula max. stress → chapter 3 of this presentation.
2. Calculation maximum spalling stress
2. Calculation maximum spalling stress

- **Introduction**
  - Nonlinear distribution of longitudinal stress $\sigma_x$ in the sections of the ‘disturbed’ anchorage zone $\rightarrow$ Navier-Bernoulli hypothesis (plane sections remain plane after bending) is not valid.
  - Nonlinear distribution of transverse stress $\sigma_y$.
  - E.g. web I-beam:

  $\rightarrow$ difficult to ‘design’ this area.
2. Calculation maximum spalling stress

- **Second half 20th century**
  - A lot of research on the tensile stresses in the transmission zone.
  - In the USA and Europe.
  - Mostly post-tensioning (higher stress concentration).
  - Impossible to present a complete overview.

- **Simple cross sections**
    E.g. Truss analogy of Mörsch:
2. Calculation maximum spalling stress

- Simple cross sections
  - Strut-and-Tie Model:

\[
\sigma_{sp} = 16 \cdot \left( \frac{e_0}{d} - \frac{1}{6} \right)^2 \cdot \frac{P_0 \cdot d^2}{e_0 \cdot l_m^2 \cdot b}
\]

Max. stress rectangular cross section:

This formula works if \(P_0\) acts outside the core of the cross section.
2. Calculation maximum spalling stress

- Simple cross sections
  - Kupfer’s method = equivalent prism analogy → equilibrium of a part of the transmission zone.

\[
\sigma_{sp} = \frac{8 \cdot P_0 \left( \frac{d^2}{6 \cdot e_0} - \frac{d}{108 \cdot e_0^2} - d + 2 \cdot e_0 \right)}{l_m^2 \cdot b}
\]

\(d'\) is chosen so that the resultant of the stresses acting at the transmission zone end is equal to the prestressing force.

→ CEB-FIB Model Code 1990
2. Calculation maximum spalling stress

Cross section hollow core slabs

- Not a simple cross section.
- Prestressing force is not distributed uniformly across the width of the slab.
- Transformation to simple cross sections (equivalent I-section).

→ Calculate the max. spalling stress with the discussed methods.
2. Calculation maximum spalling stress

- Cross section hollow core slabs
  - Transformation to simple cross sections (equivalent rectangular section).
    FEA of J.A. den Uijl (TU Delft) showed that the spalling stress of a rectangular section and a I-section are the same, as long as the relative eccentricity and the web width are the same.

\[
d_{eq} = \frac{e_0}{(e_0 - k) + \frac{1}{6}}
\]

\[
e_0 - k = \text{relative eccentricity}
\]

\[
k = \text{core radius of cross section}
\]
2. Calculation maximum spalling stress

- Cross section hollow core slabs
  - Finite element analysis
  - Analytical assessment of the spalling stresses is only approximately possible.
  - To get a better understanding about:
    - The influence of some parameters on magnitude;
    - Distribution of the stresses;

J.A. den Uijl performed finite element analysis.

\[
\sigma_{sp} = \frac{P_0}{b_w e_0} \left( 2 \left( 0.02 + 4 \alpha_e^{2.3} \right) \left( \alpha_e + \frac{1}{6} \right) \right) \left( 0.1 + 0.5 \alpha_e \right) \left( 1 + 1.5 \left( \frac{l_t}{e_0} \right)^{1.5} \left( \alpha_e + \frac{1}{6} \right)^{1.5} \right) = \text{max. stress}
\]

with \( \alpha_e = \frac{e_0 - k}{d} = \text{relative eccentricity} \) & \( l_t = \text{transmission length} \)
2. Calculation maximum spalling stress

- Cross section hollow core slabs
  - Den Uijl’s formula of $\sigma_{sp}$:
    - Web or whole section.
    - $\sigma_{sp} \leq f_{ctkj}$ = characteristic tensile strength at prestressing
    - Only for members with $d < 400$ mm.
    - Influence of upper reinforcement was not analyzed.
    - $\sigma_{sp} \leq f_{ctkj}$
      \[ 1990: \sigma_{sp} \leq \frac{f_{et,fl}}{\gamma_c} \text{ with } f_{et,fl} = \text{mean flexural tensile strength} \& \gamma_c = 1.5 \]
      \[ 2010: \sigma_{sp} \leq f_{ctd} = \frac{f_{ctk}}{\gamma_c} = \text{design concrete tensile strength} \]
3. Spalling stress according EN1168
3. Spalling stress according EN1168

For each web or for the whole section (strands/wires well distributed over the width of the element):

\[ \sigma_{sp} = \frac{P_0}{b_w e_0} \cdot \frac{15 \cdot \alpha_e^{2.3} + 0.07}{1 + \left( \frac{l_{pt1}}{e_0} \right)^{1.5}} \cdot (1.3 \cdot \alpha_e + 0.1) = \text{max. stress} \]

With \( \alpha_e = \frac{e_0 - k}{d} = \text{relative eccentricity} \geq 0 \)

\[ k = \frac{W_b}{A_c} = \text{core radius} \]

\( W_b = \text{section modulus bottom fibre} \)

\( A_c = \text{area of cross section} \)

\( l_{pt1} = \text{lower desing value of transmission length} \)
3. Spalling stress according EN1168

- Similarity with formula of J.A. den Uijl:

\[
\sigma_{sp} = \frac{P_0}{b_w e_0}.
\]

\[
\begin{align*}
\sigma_{sp} &= \frac{2(0.02 + 4\alpha_e^{2.3})(\alpha_e + \frac{1}{6})}{(0,1 + 0,5\alpha_e)(1+1,5\left(\frac{l_t}{e_0}\right)^{1,5})(\alpha_e + \frac{1}{6})^{1,5}} \\
&= \frac{15\alpha_e^{2.3} + 0,07}{1+\left(\frac{l_{pr1}}{e_0}\right)^{1,5}} \cdot (1,3\alpha_e + 0,1)
\end{align*}
\]

Rewritten with almost equal \(\sigma_{sp}\) as result (if \(l_t = l_{pr1}\)).

More background information on this transformation is welcome.
3. Spalling stress according EN1168

- Use the formula OR fracture-mechanics design shall prove that spalling cracks will not develop: study of the propagation of cracks using the method of finite elements.

- Visible horizontal spalling cracks in the webs are not allowed!

- Value of transmission length?
  - Calculated according EN1992-1-1 → rather high values.
  - Experimental research → up to 50% less!
  - Important parameter!
3. Spalling stress according EN1168

- Relative eccentricity $\geq 0$:

  \[ P_0 \text{ in core} \rightarrow e_0 < k \rightarrow \alpha_e = \frac{e_0 - k}{d} < 0 \rightarrow \alpha_e = 0 \]

  \[ \sigma_{sp} = \frac{P_0}{b_w e_0} \cdot \frac{0.07}{1 + \left( \frac{l_{pt}}{e_0} \right)^{1.5}} \cdot 0.1 \]

- Section modulus: Bottom fibre or top fibre?

  \[ W_b = \frac{I}{e_b} \quad \text{or} \quad W_t = \frac{I}{e_t} = \frac{I}{d - e_b} \]
3. Spalling stress according EN1168

- **Section modulus**: got lost in translation?

\[
W_b = \frac{I}{e_b} \quad \& \quad W_t = \frac{I}{e_t} = \frac{I}{d - e_b}
\]

- \(\sigma_{sp}\) for upper reinforcement
- \(\sigma_{sp}\) for lower reinforcement
- (max. tensile in bottom fibre) (max. tensile in top fibre)

- **Thickness of the web** \(b_w\):
  - The minimum thickness?
  - Better to use thickness at center of gravity?
3. Spalling stress according EN1168

- \( \sigma_{sp} \leq f_{ct} \) = tensile strength at release on the basis of tests.
  - Potential vs. structural strength (overestimating of strength).
    Need for a method to measure the structural tensile strength in a simple and quick way!
    → Research topic?

- Characteristic value vs. mean value.

\[ f_{ctm} = \text{mean} \]
\[ f_{ctk0,05} = \text{5\% fractile} \]

- \( f_{ctm} \):
  - \( \rightarrow 50\% \text{ is smaller!} \)
  - \( \rightarrow \text{used in the evaluation of a specific case} \)

- \( f_{ctk0,05} \):
  - \( \rightarrow \text{only 5\% is smaller} \)
  - \( \rightarrow \text{used in the design of the slab} \)
3. Spalling stress according EN1168

- $\sigma_{sp} \leq f_{ct} = \text{tensile strength at release on the basis of tests.}$
  - Points of interest:
    - You don’t know how far it is until cracking, but all slabs are subjected to a test during first lifting from the production bed.
      - stresses due to lifting or suspension must be added to become a ‘safer’ situation?
    - Spalling cracks can occur shortly (1-2 days) after production, due to the short-term creep of concrete.
    - Increasing the compressive strength of the concrete at release of prestress works at ‘both sides’:
      - Higher tensile strength.
      - Higher spalling stress, due to the shorter transmission length. $\uparrow \sigma_{sp} \leq f_{ct} \uparrow$
3. Spalling stress according EN1168

- How to deal with members with $d \geq 400$ mm?
  - FEA in the past: $d < 400$ mm.
  - Is the formula valid for $d \geq 400$ mm?

In thick members the stress distribution in the sections of the anchorage zone will be ‘more’ nonlinear than in thin members.
3. Spalling stress according EN1168

- How to deal with members with $d \geq 400$ mm?
  - Scope of EN1168:
    - prEN 1168: 1997: maximum $d = 440$ mm
      $\rightarrow$ formula of $\sigma_{sp}$ validated with experimental research?
  - More and more thicker hollow core slabs are used:
    - $d = 450, 500, 800, \ldots 1000$ mm: search the limit of application of our products
    - In practice a high risk on spalling
    - Competitor of double T floor
3. Spalling stress according EN1168

- How to deal with upper reinforcement?
  - FEA in the past: only with lower reinforcement.
  - 1st way to use the formula?
    - Replace prestress force + eccentricity of the upper and lower reinforcement by one prestress force + eccentricity and then calculate $\sigma_{sp}$?

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<thead>
<tr>
<th>$e_{0,1}$</th>
<th>$P_{0,1}$</th>
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<tbody>
<tr>
<td>$e_{0,2}$</td>
<td>$P_{0,2}$</td>
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<tr>
<td>$e_{0,3}$</td>
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Statically equivalent systems, but different $\sigma_{sp}$ because local effects are different (principle of Saint-Venant).
3. Spalling stress according EN1168

- How to deal with upper reinforcement?
  - 1st way to use the formula?
  - What in case of 2 symmetric forces (e.g. wall elements)?

Statically equivalent systems, but different \( \sigma_{sp} \) because local effects are different.

EN1168 \( \rightarrow e_{0,3} = 0 \rightarrow \sigma_{sp} = \#DIV/0! \)
3. Spalling stress according EN1168

- How to deal with upper reinforcement?
  - 2\textsuperscript{nd} way to use the formula?
    - Calculate $\sigma_{sp}$ lower reinforcement $\rightarrow \sigma_{sp, \text{lower}}$
    - Calculate $\sigma_{sp}$ upper reinforcement $\rightarrow \sigma_{sp, \text{upper}}$

$\sigma_{sp, \text{lower}}$ and $\sigma_{sp, \text{upper}}$ are located at different heights.

$\sigma_{sp, \text{lower}} + \sigma_{sp, \text{upper}}$ is not correct.
How to deal with upper reinforcement?

- 3\textsuperscript{th} way to use the formula?
  - Just ignore $\sigma_{sp}$ of the upper reinforcement.
    - probably done the most, but the negative effect is ignored!

- Positive impact of the upper reinforcement in case of thin slabs? Negative impact in case of thick slabs?
  - What’s a thin or a thick slab in this sense?

- Upper reinforcement in hollow core slabs is used:
  - In some seismic areas (e.g. New Zealand)
  - When handling is a problem
  - In wall panels (d is rather limited; +/- 200 mm)
4. Conclusion
4. Conclusion

- For $d < 400$ mm and without upper reinforcement the formula of EN1168 works fine.

- Further research is needed to find a more ‘correct/reliable’ method for calculating the maximum spalling stress in hollow core slabs with $d \geq 400$ mm and/or upper reinforcement.

On behalf of ECHO, a theoretical study was started by two students of Xios Hogeschool Limburg in Hasselt, Belgium:

- Building of a finite element model for slabs with and without upper reinforcement;
- Formulate a truss analogy (strut-and-tie model);
- Work out a generally valid formula ($d < 400$ mm and $d \geq 400$ mm).
4. Conclusion

- Ideal would be to perform an experimental research to validate the results of the theoretical study:
  - Very expensive!
  - Share practical experience of manufacturers → ‘sharepoint’ on the internet in the future?

- The design regarding spalling should be always a ‘bottom up design’ = some slabs that fails in the model, will satisfy in practice.

- Products evolve, standards should do too!
Thank you for your attention!

Questions?

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